Considerations for a Research Program on Drought in Mexico

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Abstract

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The impacts of drought in Mexico have led water authorities to define a strategy for action to diminish their costs. But the proposed actions at regional levels require a solid scientific basis on the subject to answer several of the questions that decision makers have, not only on the dynamics of climate variability, but on the context that produces hydrological, agricultural and socioeconomic droughts. This work makes some considerations on the research topics and approach to be followed in the scientific Plan for the Program against Drought in Mexico (known as Pronacose), in a risk management context. This approach requires that, in addition to monitoring strategies and the study of processes and prediction on drought, vulnerability be characterized as a dynamic and multifactorial element within the analysis on risk to drought. This approach also requires the collaboration of stakeholders from various sectors and regions, in order to define structural and non-structural measures against drought, such as early warning systems.

Keywords: Drought risk, research program, early warning system.

Resumen

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Los impactos de la sequía en México han llevado a las autoridades del agua a definir una estrategia de acción para reducir sus costos. Pero las acciones propuestas a nivel regional requieren una sólida base científica sobre el tema, a fin de responder a varias de las preguntas que los tomadores de decisiones tienen, no sólo sobre la dinámica de la variabilidad del clima, sino también en cuanto al contexto en que se producen las sequías hidrológicas, agrícolas y socioeconómicos. Este trabajo hace algunas consideraciones sobre los temas de investigación sobre sequía, sus impactos y la forma de abordarlos como parte del Plan Científico para el Programa Nacional contra la Sequía de México (conocido como Pronacose), en un contexto de gestión de riesgo. Este enfoque requiere que, además de la definición de estrategias de monitoreo, estudio de los procesos y predicción de la sequía meteorológica, la vulnerabilidad a esta condición sea caracterizada como un elemento dinámico y multifactorial. El enfoque de riesgo ante sequía necesita además de la participación de actores clave de diversos sectores de las regiones, con el fin de definir de manera conjunta las medidas estructurales y no estructurales para reducir los impactos de la sequía, como son los sistemas de alerta temprana.

Palabras clave*: riesgo de sequía, programa de investigación, sistema de alerta temprana.*

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Introduction

a) Drought Risk Analysis

Human activities and ecosystems health depend on adequate and reliable sources of water. Consequently, a meteorological drought, identified as periods of insufficient water initiated by reduced precipitation for a prolonged time (WMO, 2006), represents a natural hazard (Wilhite, 2000). There is great concern about such climatic condition since its socio-economic costs have substantially grown in recent decades (Wilhite, Sivakumar, & Pulwarty, 2014). Depending on the vulnerability context, an anomalously prolonged precipitation deficit may result in hydrological, agricultural or socioeconomic droughts. Therefore, it is important to construct programs to prevent, or at least to reduce, the negative impacts of drought by defining risk management strategies. This is one of the reasons why some United Nations agencies, such as the World Meteorological Organization (WMO) or the Food and Agriculture Organization (FAO), promote science-based actions to examine the key drought vulnerabilities, in order to define strategies to prevent or at least reduce the magnitude of drought impacts. This suggestion shows that nowadays prevention is more relevant than disaster recovery.

Water agencies around the world are improving their water management capacity in order to manage prolonged periods of water shortage resulting from drought. The ultimate goal of this effort is to create drought resilient societies and ensure food security and sustainability of natural systems (Wilhite *et al*., 2014). But this cannot be an isolated effort. "Countries need to work together to use their experiences, science and technologies to create formal national preventive policies against droughts" (United Nations, 2013). The recent prolonged meteorological droughts in northern Mexico (2010-2012), California (2012-2015) or Brazil (2014-2015) for instance, have placed a number of questions about this phenomenon that need to be addressed by the scientific community to better define water management practices under prolonged drought conditions. Various research international programs have developed in order to share knowledge and experience on how to prepare for such climatic phenomenon (*e.g.*, WCRP, 2011). Similarities and contrasts among drought events and impacts around the world may lead to better prevention programs in a context of a global water crisis (Oelkers, Hering, & Zhu, 2011). A better understanding on the mechanisms that force prolonged meteorological droughts is necessary, along with adequate characterizations of the factors that make a region or sector vulnerable to this climatic condition. This is one of the reasons why research programs on drought are international, multidisciplinary and crosswise, and with a strong component of applications on uses of climate information by sector (WCRP, 2011).

Droughts and water shortages significantly affect the lives of millions in Mexico and around the world, particularly in the agriculture, cattle ranching and hydropower generation sectors. At times, droughts also have an impact in major urban or tourism centers. The social, economical and environmental costs of the recent severe drought in northern Mexico (Rodríguez & Juárez, 2011) have led to consider public policies to reduce the impacts. The National Water Commission (known as Conagua) has developed an increased interest in understanding severe meteorological droughts to define responses to reduce the consequences. But defining what a severe drought is, or what a critical period of precipitation deficit in time is, requires a continuous monitoring of climatic conditions, as well as the characterization of the drought vulnerability context. Until recently, vulnerability was an aspect of risk that was seldom included in most analyses of hydrological, agricultural or socioeconomic droughts in Mexico (Neri & Magaña, 2015). Some qualitative descriptions of vulnerability to drought were developed but not validated (*e.g*., Conagua 2014). It is unknown if they actually explain the impacts of drought in recent years. Therefore, a risk to drought model requires a quantification of vulnerability and validation of the vulnerability model in order to identify the main factors that increase the risks of hydrological or agricultural drought (Neri & Magaña, 2015).

Several studies examine meteorological drought in Mexico, documenting episodes of precipitation deficit at regional level (Magaña, 1999; Hernández, Carrasco, & Alfaro, 2007; Escalante-Sandoval & Reyes-Chávez, 2012; Márdero *et al*., 2012; Vilches-Francés, Díaz-Delgado, & Bâ, 2014) or the climate dynamic processes that result in drought (Seager *et al*., 2009; Méndez & Magaña, 2010). On the other hand, agricultural drought has been mainly analyzed in terms of its impacts (Bellon *et al*., 2004), or in terms of options to tackle it (Acosta *et al*., 1999). However, it is necessary to develop studies to

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understand how droughts affect different types of agro-ecosystems, coupling climate information and the responses of vegetation. Numerous studies document the history of drought impacts, using approaches based on proxies, such as dendrochronology (Villanueva-Díaz *et al*., 2014), or historical documents (Endfield & O´Hara, 1999; Liverman, 1999; Garza, 2002; García-Acosta, Pérez, & Molina, 2003; Contreras, 2005). Some others discuss the costs of drought in the agricultural or cattle ranching sectors in Mexico (*e.g*., Ortega-Ochoa, Villalobos, Martínez-Nevárez, Britton, & Sosebee, 2008; Eakin, 2007). But they rarely refer to vulnerability in a multifactorial and dynamic manner.

The scientific literature on the hydrological drought in Mexico is also abundant, with reference to the problems on water management under water stress conditions and precipitation deficit in various regions (Pereyra & Sánchez, 1995; Mendoza *et al*., 2005; Ortega-Gaucin, 2012). They basically document changes in streamflow, water reservoir levels or soil moisture deficit, considering these are direct impacts of meteorological droughts, in a sort of natural paradigm perspective (Stallings, 2003). Bout some hydrological droughts may occur even without a meteorological drought, depending on the water management practices. Finally, there are numerous aspects of the socioeconomic drought that also need to be addressed in a risk analysis context, in such a way that results may be used to improve policies and actions to reduce the impacts of drought in Mexico for instance, at the urban level.

The National Program against Drought, known as Pronacose, was developed in 2012 and aims at inhibiting or reducing the impacts of drought by means of preventive actions. In particular, the Program on Preventive Measures and Drought Impact Mitigation, known as PMPMS, is a component of Pronacose whose goal is to implement specific measures to reduce the impacts of meteorological drought, based on adequate drought information on the hazard and the vulnerability at the sub-basin level. At present, the characteristics of the actions depend on the severity of the meteorological drought according to the scale presented in the North American Drought Monitor (Table 1). However, a more adequate measure of hydrological and agricultural droughts in it has not been adjusted to correspond to actual impacts in Mexico. The PMPMS requires better estimates of risk in order to define when and what actions should be implemented to efficiently prevent or reduce the magnitude of drought related disasters. The need for such risk estimates has led to a number of scientific questions about droughts and their impacts in various regions and socioeconomic sectors of Mexico. It is necessary to define a Drought Research Program in order to address scientific issues about monitoring, processes and prediction, drought risk analysis and management, and communication. Therefore, a scientific research plan on drought for Mexico is required, that addresses the scientific issues on meteorological drought but also, that examines the causes of hydrological, agricultural and socioeconomic droughts in order to present relevant information to decision makers in Mexico.

b) Objective

The objective of this work is to propose some elements for a Scientific Research Plan on Drought for Mexico, which serve to generate knowledge on key aspects of this climatic conditions and its impacts that allow implementing basic actions of the Pronacose-PMPMS program. The emphasis of the Scientific Plan is on the need to better understand the physical and dynamical processes of climate variability that lead to drought, on the schemes for improved seasonal predictions of meteorological droughts in Mexico, as well as on ways to quantify the vulnerability to drought factors that result in risk of hydrological, agricultural and socioeconomic droughts. The identification of the vulnerability factors and risk to drought models will serve to better define preventive actions within Pronacose-PMPMS.

As in several countries with programs on drought risk management, the Drought

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Table 1. Drought Severity Classification at National Drought Mitigation Center.

			Range				
Category	**Description**	**Possible impacts**	**Palmer Drought Index**	**CPC Soil Moisture Model (percentiles)**	**USGS weekly streamflow (percentiles)**	**Standardized Precipitation Index (SPI)**	**Objective Short and Long Term Drought Indicator Blends (percentiles)**
D0	Abnormally dry	Going into Drought: Short term dryness slowing planting, growth of crops or pastures. Coming out of drought: some lingering water deficit; pastures and crops not fully recovered	-1 to -1.9	21 - 30	21-30	-0.5 to -0.7	21 - 30
D1	Moderate drought	Some damage to crops; streams, reservoirs or wells low, some water shortages developing or imminent; water-use restrictions request	-2.0 to -2.9	11 - 20	11 - 20	-0.8 to -1.2	11 - 20
D2	Severe drought	Crop or pasture losses likely; water shortages common; water restrictions imposed	-3.0 to -3.9	6-10	6-10	-1.3 to -1.5	6 - 10
D3	Extreme drought	Major crop/pasture losses; widespread water shortages or restrictions	-4.0 to -4.9	3 - 5	3 - 5	-1.6 to -1.9	3 - 5
D4	Exceptional drought	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells creating water emergencies	-5.0 or less	0 - 2	0 - 2	-2.0 or less	0 - 2

Research Plan for Mexico should start by defining the problems on the subject and the existing capacities for monitoring, understanding processes and prediction. Some of the scientific questions should be formulated to obtain multidisciplinary assessments, particularly with respect to the evaluation of drought vulnerability at the regional and sectorial level. The drought research strategy should be part of a more general scientific agenda to understand climate variability and climate change. Although progress has been made in the understanding some aspects of drought, it is still necessary to construct risk management and decision making schemes that motivate stakeholders to take actions that prevent or at least reduce some of the negative effects of droughts. Structural and non-structural measures based on drought risk analysis should lead to the development of early warning systems. In the end, the Drought Research Plan should make the Mexican society and its socioeconomic sectors more drought re-

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silient with better water management strategies, in other words, drought research should be part of a more ambitious scientific plan on improved water management.

Drought research perspectives for Mexico

a) Drought Monitoring in a Risk Management Context

The study and management of drought have been constructed in terms of four basic lines of study: meteorological, hydrological, agricultural, and socioeconomic droughts (Wilhite & Glantz, 1985). The first one corresponds to a form of natural climate variability, but the last three approaches involve water management practices and consequently, include anthropic factors that should be taken into account. Therefore, the meteorological drought requires measuring physical parameters, but the other types of drought also require documenting social and economical elements (*e.g.*, Neri & Magaña, 2015).

In many parts of the world drought monitoring strategies are not limited to gather and displaying precipitation or temperature data, or to construct averages and anomalies in order to define the characteristics of a drought. Having the ability to monitor droughts is part of the climate variability operational analysis, a systematic procedure to promote timely actions to reduce the impacts of climatic anomalies. The monitoring of drought should include the manifestations of hydrological, agricultural and socioeconomic droughts, by measuring atmospheric, surface and subsurface parameters. In contrast to other meteorological hazards, droughts need to be characterized about their slow onset, evolution and demise, as well as their spatial extent and intensity.

Droughts are complex, large-scale phenomena involving air-sea and -land surface processes. In general, socio-ecosystems are resilient to short-term negative precipitation anomalies, but seasonal or prolonged droughts (more than a year duration) may turn into a socioeconomic and environmental crisis in countries that do not have adequate water management strategies. They are more noticeable in arid and semiarid regions of the world since limited water availability results in more frequent and prolonged periods of hydric stress. But meteorological droughts also occur in humid areas, where they may last from weeks to months (Dai, 2011). Droughts are not only related to water scarcity, but also to above-normal temperatures, which enhance soil moisture deficit. Although progress has been made on the understanding of the dynamics of meteorological droughts (Sheffield, Wood, & Roderick, 2012), there are numerous key unsolved issues that prevent water managers from defining more efficient water management policies for dry periods. These issues have to do with inadequate ways of characterizing, monitoring and forecasting meteorological drought and their impacts, in such a way that societies can move from drought disaster response to drought risk reduction.

Meteorological droughts are usually defined on the basis of the degree of dryness, in comparison to some "normal" or average amount, and the duration of the dry period. Definitions of meteorological drought should consider regional climatic conditions to define what is considered as anomalous. In regions like Mexico, prolonged droughts are at least a synoptic scale phenomenon that may be monitored by the current network of surface weather stations. The use of statistics in individual stations to represent "local droughts" may be considered inadequate since the existence of persistent negative anomalies in precipitation affect a larger extension than only a small location. This may not be the case when hydrological, agricultural or socioeconomic droughts are evaluated since vulnerability may be due to local factors, which in turn are determinant in the magnitude of the impacts of a drought.

Some of the most severe droughts of the twentieth century in the world, including the one in the 1930s known as the "Dust Bowl" drought in North America, have been explained

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in terms of natural factors and human induced forcing (*e.g*., Cook, Miller, & Seager, 2009). But the analysis of the dynamics of drought and its impacts is based on the existence of adequate data to characterize its evolution by means, for instance of indicators. As part of the monitoring activities, keeping track of drought indices or parameters is a priority (Svoboda *et al*., 2002), in conjunction with adequate observations of large-scale conditions that are known to force drought (*e.g.*, sea surface temperature, soil and land use conditions, etc.). Analyses based on climatology, hydrology, and satellite-derived data are necessary to characterize the various elements of drought dynamics, its evolution and its impacts.

A reliable drought-monitoring scheme requires continuous precipitation and historical databases. The statistics used to define the intensity of a meteorological drought are related to the climate of the region under consideration. For instance, some definitions of meteorological drought identify dry periods on the basis of the number of days with precipitation less than some specified threshold. This measure is most appropriate for regions where precipitation occurs year round, such as a tropical rainforest, humid subtropical climate, or humid mid-latitude climate. But meteorological drought in regions with a monsoonal climate, *i.e.*, with a well defined seasonal rainfall, and dry periods are better characterized by making reference to accumulated precipitation below a threshold value. In some regions, drought intensities and length may relate to actual precipitation anomalies with respect to average amounts on monthly, seasonal, or even longer time scales.

The use of modern techniques to obtain and assimilate climatic data from remote sensors is an important part of climate analysis. The monitoring of meteorological drought for Mexico may rely on the surface weather station network complemented with remotely sensed estimates of precipitation, temperature and atmospheric humidity, for instance. The use of data assimilation techniques becomes necessary to have gridded estimates of precipitation or other meteorological parameters, whose reliability may be evaluated. Satellite estimates have a relatively short history but in any event, they should be incorporated to complement in situ measurements. Producing frequent (*e.g*., daily) precipitation fields from in situ and satellite data by means of algorithms constitutes a mean to monitor rainfall in regions where a single event, such as a tropical cyclone, may radically change the statistics of precipitation. For instance, Hurricane Alex in northeastern Mexico in late June 2010, made the first signals of the 2010-2012 meteorological drought in Mexico "blurred". Among the global precipitation estimates, data from the Tropical Rainfall Measuring Mission (TRMM) or the CPC Morphing Technique (CMORPH) (Joyce, Janowiak, Arkin, & Xie, 2004) have been used to generate high spatial and temporal resolution precipitation fields for Mexico (Magaña *et al*., 2012). The use of combined CMORPH and station data shows higher spatial coherence with impact data, as for instance the Normalized Difference Vegetation (NDVI) anomalies for August 2011 (Figure 1). The use of Conagua station precipitation data shows precipitation in regions where other sources of gridded precipitation data, such as the ERA-interim data indicate negative precipitation anomalies. For instance, in northwestern Mexico (Sonora and Chihuahua), ERA interim analysis indicate a dominant negative anomaly, contrary the positive precipitation anomalies obtained with the estimates with by rain gauge data and CMORPH estimates, and observed in the positive NDVI anomalies. Therefore, monitoring meteorological drought requires various sources of data. Temperature and atmospheric humidity data also provide information on the characteristics of meteorological drought, as well as other parameters such as surface pressure, wind and radiation.

One of the most widely used drought indices is the Palmer Drought Severity Index (PDSI) that describes intensity, duration, and spatial extent of an event (Palmer, 1965). The PDSI refers to anomalies in the supply and demand of water using monthly data of precipitation,

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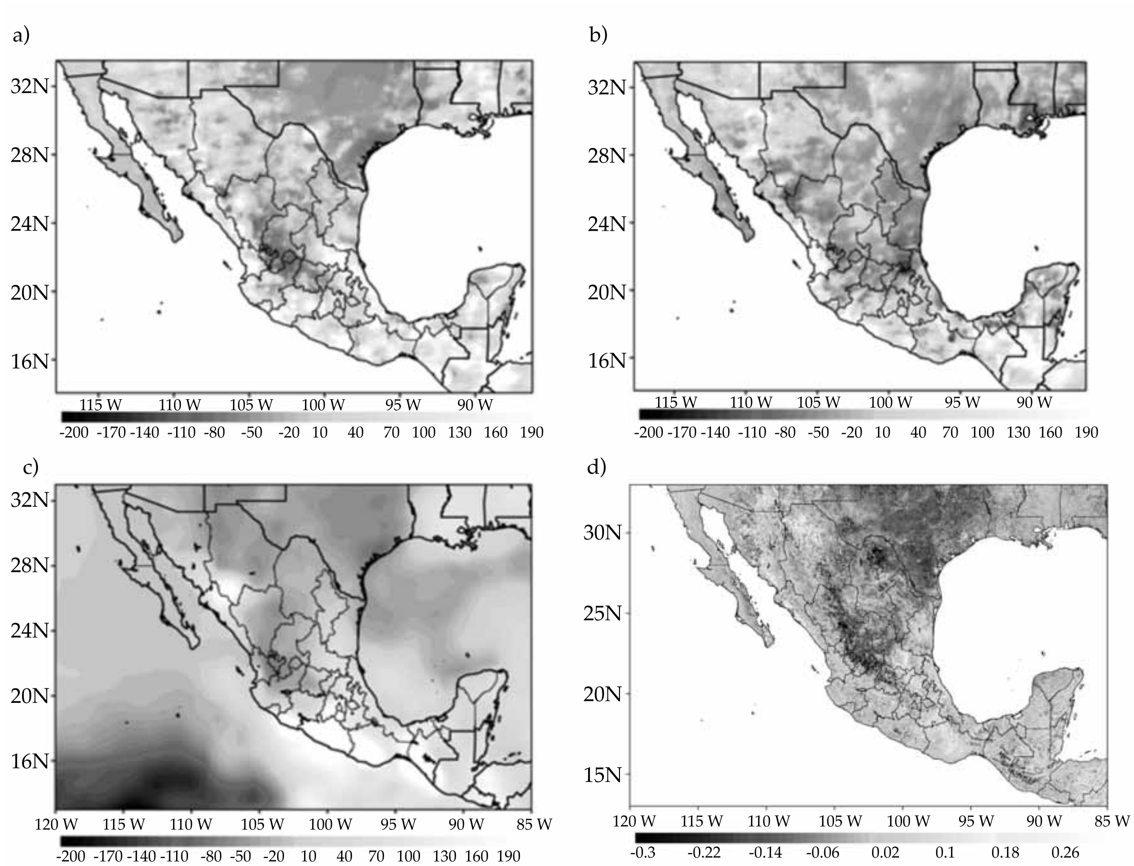

Figure 1. Monthly precipitation anomaly (mm), a) for July 2011 and b) August 2011 resulting from the combined data of the Conagua surface station network and CMORPH estimates. c) Monthly precipitation anomaly (mm) for July 2011 from the ERA-interim (ECMWF) data, and d) NDVI anomalies for August 2011.

temperature and soil moisture. However, the PDSI has mostly been used to characterize agricultural droughts (Hayes, Svoboda, Wilhite, & Vanyarkho, 1999), and not so frequently meteorological droughts. The PDSI limitations led to the development of the Standard Precipitation Index (SPI), based on precipitation data only (McKee, Doesken, & Kleist, 1995). The SPI is commonly used around the world to provided operational drought-monitoring information in near real-time (WMO, 2009). The SPI allows a relatively direct interpretation of short-term and long-term droughts but requires a long-term precipitation database. This is available for of Mexico and its calculation is easy to obtain by transforming the cumulative distribution function of precipitation into a normal distribution with a mean zero and standard deviation one. A precipitation total for a specified time period may be identified with a SPI value. Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation. The magnitude of departure from zero represents a probability of an accumulated precipitation in a time period. Given the probabilities in a normal distribution, an interpretation of the SPI is that values less than −1.0, -2.0 or -3.0 have probabilities of 16, 2.5 or 0.5%. The monitoring of drought (SPI) is nowadays given in terms of the SPI, but is usually complemented with reference to other measures.

In Mexico, drought information makes reference to the North American Drought Monitor, that combines climatic data through a variety of data-based drought indices and indicators and "local expert input" to estimate the impacts of meteorological droughts in terms of indices. The map of the Drought Monitor corresponds to four levels of drought intensity (ranging from D1 - D4) and one level of "abnormal dryness" (D0) (see Table 1). But the reference of the Drought Monitor to areas experiencing agricultural or hydrological drought impacts basically extrapolates the knowledge about drought risks in these sectors from the conditions in the United States. The indication of hydrological or agricultural droughts is not always referenced to an actual analysis of impacts in these sectors in Mexico. Therefore, it is necessary to consider a new approach to define when a meteorological drought reaches critical levels to become a hydrological or agricultural drought.

Precipitation deficit negatively affect surface or subsurface water supplies (*i.e*., streamflow, reservoir and lake levels and groundwater) and may result in hydrological droughts. However, in some cases hydrological droughts may occur due to poor water management, even when precipitation is within its normal range. Water management problems may at times explain hydrological, as well as agricultural and socioeconomic droughts. Therefore, in a risk context, monitoring hydrological or agricultural droughts should consider the natural hazard, as well as the vulnerability context (Neri & Magaña, 2015). For instance, monitoring a hydrological drought should refer to measures of surface and subsurface water availability (streamflow, soil moisture, dam or lake levels, aquifer conditions) but in a more complete manner, it should also address issues related to supply and demand. This means that monitoring should include data on natural water availability, as well as on vulnerability indicators to reach a diagnostic on the severity of hydrological drought. The monitoring of water supply and demand may allow determining the anthropic factor that leads to a hydrological drought, but it also serves to determine preventive actions to inhibit the occurrence of such disaster.

Given that long-term observations of soil moisture are scarce, derived data with models becomes a valuable alternative to obtain information (Narasimhan & Srinivasa, 2005). Hydrological droughts usually lag meteorological droughts and their extent, duration and severity depend on water management practices in a watershed or basin. It is necessary to complement the in situ measurements with satellite estimates of soil moisture and groundwater (Houborg, Rodell, Li, Reichle, & Zaitchik, 2012). Some satellite-derived data on soil moisture also prove to be useful to estimate humidity deficit in agriculture or other ecosystems, for instance using NDVI. The lag between the precipitation deficit and its signal in surface or subsurface water deficit should be determined through adequate monitoring. It may be of the order of a few days to weeks to months, and turns to be important in a preventive decision-making. The characterization of hydrological droughts requires information on the whole hydrological cycle and an adequate representation using data assimilation methods. The use of remotely sensed data, including satellite groundwater monitoring, will greatly improve the estimates of water supply. Monitoring streamflow drought and issuing early warnings can result in efficient prevention actions as part of the water resource management. As in the case of the SPI to characterize meteorological drought, the Standardized Runoff Index, may serve to identify threshold values that may lead to a hydrological drought.

As a form of hydrological drought, streamflow droughts have been given more attention since they may lead to a number of negative impacts for the society and the environment. The survival of ecosystems depends on their homeostasis and resilience to water deficit and hydrological droughts, which may have profound effects in the environment (Lake, 2011). This aspect of drought on ecosystems is seldom analyzed in Mexico, except when it relates to forest fires. The drought events that had a large impact in terms of forest fires are related to the

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occurrence of intense El Niño conditions, as in 1997-98 (Magaña, 1999) or the prolonged meteorological droughts in northern Mexico, as in Coahuila in 2011. Forest fire activity in Mexico is modulated by the vulnerability context (Galindo, Barrón, & Padilla, 2009). Consequently, the deficit in precipitation, atmospheric and soil moisture, temperature anomalies, along with vulnerability conditions, create drought risk for the development of wildfires.

Besides the reduction in the flow of rivers and soil moisture deficits, meteorological droughts also contribute to agricultural losses. Agricultural droughts are related to seasons when the water requirements are not met due to precipitation deficit, large potential evapotranspiration, soil water deficits, and reduced groundwater or below normal irrigation reservoir levels. According to the US National Drought Mitigation Center "a good definition of agricultural drought should be able to account for the variable susceptibility of crops during different stages of the crop development, from emergence to maturity". It should also consider the capacity to adapt to unfavorable climatic, economic or environmental conditions, which changes from region to region for instance, between Mexico and the US. Therefore, the same indices to define how a precipitation deficit may result in agricultural drought should be evaluated at the regional context considering local vulnerabilities and capacities. Determining the causes of an agricultural drought requires establishing the socio-economical aspects and public policies in the sector. Two similar meteorological drought events may have contrasting impacts depending on the vulnerability context in which they occur. Therefore, if the goal is to prevent an agricultural drought or to diminish its impacts, the monitoring efforts should consider a complete risk evaluation. When hydrological and agricultural droughts are more severe or prolonged than a critical level, water to support food crops may not be enough to produce vegetables for people, or grass and grain for livestock and poultry. This may be the beginning of a serious socioeconomic impact. There is no unique way to define the magnitude of an agricultural drought since it may be given in terms of the area or the percentage of crops affected, as well as the social or economic costs of the losses. Even more, one of the main challenges in defining the magnitude of an agricultural drought is to separate the observed impacts related to precipitation deficit, from other natural or anthropic hazards. This is a key issue that relates drought with the Mexican economy, since the impacts are related to the losses in this sector due to low production and the food imports that are necessary.

The socioeconomic drought corresponds to low water availability for daily activities of the population. A socioeconomic drought may be considered the final stage of a meteorological drought, when vulnerability conditions are high enough as to result in a severe water deficit that impact at the urban level. The potable water provision may be compromised under social drought conditions, if no adequate plans exist to respond to potable water shortages. As the population and per capita consumption grow, the demand for economic goods also grows and the chances of a socioeconomic drought increase (Wada, Van Beek, Wanders, & Bierkens, 2013). This may be a reason why droughts at the urban level appear to be more frequent nowadays. In addition to precipitation deficit, socioeconomic droughts may also result from increasing demands and poor urban water management practices. Socioeconomic droughts are highly related to water management practices at the urban level and consequently, they involve societal perception of risk to below normal precipitation. Analyzing the vulnerability of urban centers to drought may lead to structural and non-structural measures aimed at reducing the impacts in case of meteorological droughts. In large urban centers of Mexico, the water crisis makes the highly vulnerable to drought. The extremely high pressure on water of Mexico City led to a social drought in December 2009, even without the occurrence of a real meteorological drought. The positive trend in precipitation in the Mexico Valley does not compensate for the

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increasing demands of potable water and consequently, social droughts are expected to be more frequent and severe unless structural measures to reduce the water crisis be implemented.

The lack of clean water for drinking, public sanitation and personal hygiene results in a wide range of diseases. Therefore, social droughts may have to do with not enough quantity and quality of water in urban environments. In extreme situations, the social impacts of drought may also correspond to thirst, hunger and famine. When water supplies are scarce due to drought, the competition for this natural resource may lead to social conflicts (Endfield & O´Hara, 1997; Castro, Kloster, & Torregrosa, 2004) that need to be controlled. Drought may also force many people to migrate in search of more favorable living conditions, with access to water, food, and without the disease and related social conflicts. Under drought conditions, bush and forest fires lead to major environmental and social disasters. Wildfires may affect communities, their health and their property. The emissions of wildfire result in poor air quality that increases the risk of respiratory diseases. The impact of droughts on health is dependent on the socio-economic environment that can influence the resilience of the population. Poor health, poverty, and conflict are additional contributing factors to the impact of drought. Forest fires emissions are an aspect of drought directly related to drought that may extend to several kilometers away from the wildfire, affecting numerous communities. Wildfire prevention should be examined in a risk context, considering dry environmental conditions, but also the socioeconomic context favors the occurrence of these events.

There are also important social aspects of drought for human activities that relate to anxiety or depression about the economic losses or conflicts among people when there is not enough water (*e.g.*, Dean & Stein, 2007). Frequently, drought forces people to radically change their lifestyle, including people´s perception on the value of water. Such changes in people´s behavior frequently lead to more efficient use of this resource and flexibility to accept new water public policies. This was the case of the Mexico City Metropolitan Area in 2009 when water authorities were announcing a severe water crisis (See Restrepo in *La Jornada*, http://www.jornada.unam.mx/2009/08/24/opinion/018a2pol). Even more, water managers and authorities may take this opportunity to implement public policies on the efficient use of water considering changes in tariffs for potable water in all sectors and regions.

Drought also affects the environment in several ways. The ecosystems health depends on water quantity and quality. Under drought conditions, the food supply reduces and habitats are affected. Even more, extreme maximum temperature may induce stress in the comfort standards of several animal species. In some ecosystems, the damage is temporary and resilience allows ecosystems to recover, i.e., the water and food supply return to normal conditions. However, prolonged or severe droughts may have a permanent negative impact. For instance, some aquatic ecosystems may disappear and alter the surrounding regions, even when rains recover. Other effects of drought on the ecosystems include diseases in plants and animals, migration of wildlife, loss of wetlands, erosion and loss of soil quality. Some of the negative impacts of drought may be exacerbated when other anthropic pressures exist on the ecosystems. In most ecosystems of Mexico, meteorological drought is not equivalent to wildfires. However, slash and burn practices in traditional agriculture may result in higher risk of wildfires under drought conditions.

The impacts of drought may be quantified in terms of the economic costs. People and economic sectors generally pay the costs of drought with economic assistance from government agencies. Most evaluations on the economic impacts of drought refer to the direct costs of the disaster, such as loss of crops, irrigation or wells to pump water from the aquifers. There are also payments to make for food and water to maintain farm activities, for instance. But indirect costs related to drought should also be

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taken into account, for instance, those related to supplies to maintain the activity, as a mean of adaptation to an anomalous climatic conditions (water pumps, fertilizers, etc.). In countries that highly depend on hydropower generation, diminished access to water can make them experience increased costs of electricity due to reduced streamflow and dam levels. Hydroelectric power generation companies are also affected in their finances since they may have to spend more on alternative fuel sources, when hydropower generation is not enough. River navigation may turn difficult affecting commerce and transportation. In the Panama Canal, the size of ships has to be limited due to hydrological drought in the lakes that provide water for the functioning of the locks, as under El Niño conditions (Magaña, 1999). However, drought may also represent business opportunities for some that may provide goods and services that substitute those that are missing due to drought.

The impacts of droughts are not always easy to determine since the corresponding vulnerability factors are seldom considered as part of a risk analysis. For instance, prolonged droughts during 2000-2002 and 2010-2012 had similar magnitudes and spatial extent over northern Mexico, but contrasting socioeconomic impacts due to different vulnerability contexts. Therefore, drought related disasters should be explained considering the vulnerability context in which they occur. An adequate identification of vulnerability to drought factor is necessary not only to explain disasters, but also to define the most efficient risk management practices, as to prevent their negative effects. At present, most countries only respond to droughts by providing financial assistance to recover from the economic losses (Wilhite *et al*., 2014).

In summary, monitoring of droughts is no limited to physical parameters, but should include indicators of the social, economical and environmental conditions that create a context of vulnerability. Such context modulates the magnitude of risk and consequently, influences the magnitude of the impacts. Creating a risk function for hydrological, agricultural or socioeconomic drought may also serve to monitor the efficiency of various measures aimed at reducing vulnerability and risk. The definition of lead and lag times may well define some of the characteristics of the monitoring schemes and the data bases to be created to examine processes associated with drought or the quality of the predictions of droughts and impacts.

b) Processes and Prediction of Droughts

Climate prediction provides opportunities to increase the lead times of early warning systems. Scientists have made significant advances in understanding regional interannual climate variability, mainly based on considerations of air sea interactions and climatic teleconnections, as those related to El Niño Southern Oscillation (ENSO) (see Díaz, Hoerling, & Eischeid, 2001). But the potential for improved drought predictions in the near future varies from region to region, season to season and on the dominant climatic regime. The relationships between sea surface temperature (SST) anomalies and regional climate variability has led to the development of empirical and dynamical seasonal climate forecasts, mainly for the tropical and subtropical regions. In the extratropical regions however, current long-range forecasts are of limited reliability and only few ENSO-precipitation relationships exist to explain part of the climate variability in the midlatitudes. But low climate predictability should not prevent stakeholders from defining drought risk management strategies. By means of structural measures, sectors may become less vulnerable and more resilient to drought. If no drought risk management strategies are implemented, prolonged meteorological droughts may affect more people than most other natural hazards.

It is not clear if droughts around of the world are becoming more frequent, but several studies project that droughts may occur more frequently in relation to climate change (Dai, 2013; IPCC, 2013). Most of the climate change scenarios project a drier climate but also consider the large

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uncertainty on projections of the hydrological cycle. Caution or uncertainty on the projections of drought under climate change arise from the fact that some studies indicate that droughts are becoming less frequent and intense over parts of the world, for instance over most of the US (Andreadis & Lettenmaier, 2006; McCabe & Wolock, 2015). Climate change may not produce more droughts, but it could exacerbate them and it will probably expand their domain in the subtropical dry zone. Paleoclimatic studies on drought are becoming more relevant to examine how the climatic extreme is changing in the time scale of centuries. Several of them indicate that meteorological droughts, like the ones observed in recent decades, have always been part of natural climate variability. In particular, paleoclimatic studies about droughts have become more relevant since it is not clear if droughts are becoming more frequent, intense or prolonged over Mexico (Villanueva-Díaz *et al*., 2007).

Understanding the dynamical processes of climate that result in drought is a fundamental step to gain confidence on any projection about drought for the future. The use of climate model output to conclude on what the future drought activity will be like in Mexico may fall on the realm of speculation and may not add additional information on how to prepare for such events. An analysis on the low frequency variations of regional climate in Mexico, the external forcing mechanisms, the internal variability of climate, and the role of human induced changes in climate are among the process analyses that are required to document the causes of meteorological droughts in the past, but also, to evaluate the capacity of climate models to simulate periods of prolonged precipitation deficit.

Despite advances in the understanding of drought, the current capabilities of monitoring and prediction are not up to the needs of users, particularly regarding quality forecasts at the regional level for decision-making (Quan *et al*., 2012). But in the particular case of droughts in Mexico, there is a broad spectrum of dynamical problems to be addressed in order to determine their characteristics. It is known that SST anomalies act as a forcing mechanism to modulate climate variability over most of Mexico, but the way in which such signals are related to changes in the precipitation require examining the dynamics of the anomalous atmospheric circulations (Méndez & Magaña 2010; Seager *et al*., 2009). Changes in the intensity of subsidence, or in the flux of water vapor need to be examined on various temporal and spatial scales. The role of moisture flux from the Intra Americas Seas (IAS) into Mexico appears to involved transient mean flow interactions, difficult to reproduce by climate models. In addition, a single tropical cyclone entering to Mexico may completely change the statistics of climate in a few days. In this way, even in the middle of a drought period, precipitation anomalies tend to be positive, as in the summer of 2010 in northeastern Mexico. Current climate models do not have the skill to produce this type of phenomena and consequently, there are problems in reproducing meteorological drought conditions over Mexico. Domínguez (2012) found that there are higher probabilities of tropical cyclone formation over the IAS when drought conditions occur over northern Mexico.

Within the broad spectrum of research on drought, the needs of users have to be taken into account. This means that the connection between meteorological and hydrological, agricultural and socioeconomic droughts have to be determined. It is not only a matter of examining by means of data or numerical models the signals of streawflow reduction, soil moisture deficit, hydroclimatic requirements of crops, etc. It is necessary to consider the vulnerability context that results in some of the anomalous conditions in the water and agricultural sectors. So, the need to consider a multidisciplinary approach to these problems is becoming more relevant when the objective is to provide useful information to decision makers within Pronacose, for instance. Those studying the basic the physical and dynamical mechanisms of drought and those involved in designing new tools for drought monitoring and forecasting with operational and service purposes, should consider the

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drought problem in its socioeconomic dimension as well, since this is the way in which some dry spells may turn into an adverse situation for sectors and people. Thus, drought has a wide range of impacts depending on the scale of the event and which some components of the hydrological cycle are affected by an anthropic modulating effect. The history of drought impacts is a useful context to show the dynamics of vulnerability and risk to this phenomenon (García-Acosta *et al*., 2003).

Meteorological, hydrological and even agricultural drought forecasting begins with adequate analysis obtained from climate models, which makes them an essential tool for planning. However, climate models quality needs to be evaluated in order to determine how important seasonal climate forecasts can be in the planning process, particularly in terms of drought information. Climate models tend to adequately predict seasonal dry periods over most of the Mesoamerican and part of northern Mexico by using ENSO - regional precipitation dynamics or statistical relationships (Magaña, Vázquez, Pérez, & Pérez, 2003; Seager *et al*., 2009). However, some regions do not show significant predictability during some part of the year. The North American Monsoon and the corresponding rains over northwestern Mexico are still a subject of study when the objective is to have useful seasonal forecasts (Higgins & Gochis 2007; Ray *et al*., 2007). The link between meteorological and hydrological modeling has been the goal of several groups around the world (*e.g*., Mishra & Singh, 2010). There are also efforts to produce models that simulate the effects of climate on agricultural productivity around the world (Boken, Cracknell, & Heathcote, 2005). But in each case, the regional characteristics on local management in a specific sector have to be addressed to provide useful predictions of the sector under analysis. A drought risks analysis in the agricultural or hydrological fields benefit though from the modeling initiatives when they are complemented with regional information on uses of the information and local water management practices.

In Mexico, meteorological droughts have seriously affected the socio-economic sectors and the environment, especially in the center-north of the country (Garcia-Acosta, 2003; Magaña & Neri, 2012). The arid and semi-arid conditions prevailing in these regions of Mexico lead to significant losses in agricultural and livestock activities under prolonged drought. In the world, the impacts of drought include migration and the abandonment of agricultural subsistence activities (Lee, 2014). Short-term droughts, such as associated with El Niño, have negative consequences mainly in seasonal agriculture or forestry (Delgadillo-Macías, Aguilar-Ortega, & Rodríguez-Velázquez, 1999). Prolonged meteorological and hydrological droughts, as occurred between 2000 and 2002, generated difficulties in complying with the binational water treaties between Mexico and the United States. Drought in North America between 2010 and 2012 is considered the most serious, with contrasting impacts in Mexico and the United States (Combs, 2012).

It is clear that the objective of a program like Pronacose is not only to have seasonal climate diagnoses and predictions for specific sector, but also to have a number of options to ameliorate the impacts of drought in a preventive sense. Impacts of drought can be reduced if there are warnings (based on predictions) and alternatives for the most vulnerable socioeconomic sectors. National drought policies to reduce the negative impacts of droughts have been developed in countries such as United States, Australia and South Africa they have developed (*e.g*., Wilhite *et al*., 2014). Most of them tend to create more resilient sector or groups, focusing on the subsequent impact interventions by providing economic assistance to those affected. But the goal is to have preventive programs to reduce vulnerability, including the establishment of comprehensive early warning systems from improved seasonal forecasts and risk awareness on drought (Steinemann, 2006). Responses to drought warnings include optimizing the use of water in households, agriculture, livestock and industry, increasing water storage and improving distribution infrastructure (UN-ISDR, 2007).

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c) Drought Risk Analysis and Prevention Schemes

The identification of possible actions to be taken during the drought and the need to support decision makers are important challenges and have been of interest for many years (Walker, Hrezo, & Haley, 1991). Moving from the generation of climate forecasts to actual applications of climate information may consider: 1) Developing drought forecasts and relevant climate information for decision making should be in a risk management context; 2) It is necessary to have a continuous dialogue between drought information providers and users of the information; 3) the effective communication of drought should be in terms of risk scenarios, including potential impacts, costs, and feasible actions to reduce the potential impacts, and 4) a post-event evaluation of the value of the information and the actions taken during the event that demonstrate usefulness. It is common to examine ways to have regions and sectors better prepared to deal with drought by improving water use information, with clear goals and priorities on water uses that promote water conservation. But the achievement of these goals should be based on a water governance project.

A drought risk analysis is a way to better understand a region's drought vulnerability and identify the appropriate mitigation actions to take. Only few drought risk assessments have been conducted for Mexico at the regional level that can lead to structural and non-structural measures to reduce vulnerability. Despite the importance of drought for Mexico, relatively few studies have been conducted to better understand its regional meteorological, economic, social and environmental aspects from a risk analysis perspective. So far, most analyses on the subject only focus on describing the abnormal conditions hydro-climatic parameters and their impacts in sectors such as agriculture and cattle ranching. A drought risk function should be evaluated using information on the impacts of drought for recent events. There are few studies on the impacts of droughts in Mexico, which compare the negative effects from one event to another, explaining social, economic or environmental impacts considering different vulnerability factors, maintaining the dynamic and multifactorial the essence of vulnerability. For instance, the 2010-2012 drought in Mexico had an economic cost of the order of three billion dollars, thousands of people affected (agriculturists, cattle ranchers) and environmental consequences such as the forest fires in the spring of 2011 in the state of Coahuila in northern Mexico (Magaña & Neri, 2012). These impacts contrast with those during the 2000-2002 drought, which were mainly related to the failure of the Mexican authorities to fulfill the 1944 US-Mexico Water Treaty.

There are multiple requests for information on droughts in time scales longer than a season. Prolonged droughts or drought activity on time scales of decades are becoming important topics for research. Of course, the potential impacts of climate change in relation to drought are also part of such interest. But as a first step in Mexico, information on changes in the water cycle in time scales of less than a few years may be enough to change the paradigm in which water management under drought is conducted in Mexico. Several decision makers (water managers, energy sector, farmers, etc.) may look more carefully at drought impact scenarios as long as they are expressed in terms of elements of interest for the specific sector of their concern. From the user's perspective, the relevant information for drought management depends on what is being at risk. In water availability for example, the key element can be water in dams. In this case, the predictions of that specific hydrological variable is much more relevant than, for example, forecasts of seasonal rainfall, or drought indices. It is therefore necessary to conduct research on how to produce and communicate such relevant information in order to quantify its impacts in the decision-making process as expected within Pronacose.

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d) Communication on Drought in a Decision Making Process

The use of information on drought by decision makers should show some tangible benefit, or at least a potential benefit. Information has value when it is disseminated in such a way that the end-users get the maximum benefit in applying its content. Climatic or drought information is part of a continuum that begins with scientific knowledge and understanding and ends with evaluation of the information. There are several proposed means to communicate climate information to stakeholders, but the most adequate one for a particular sector or region should be determined. The processes of communicating information about drought is not limited to provide climate or impacts scenarios on hydrological or agricultural drought, but should include capacity building to interpret messages. Therefore, the communication process involves identifying the user´s community and an adequate mean to interact with it. The communication process should also be maintained before, during and after a drought to induce secure water management practices. It varies in each stage, but the message should lead to form a sector in which stakeholders know: when there is a drought, who is in charge of specific actions; means to change water allocations and uses, and schemes to verify that actions are implemented.

Several initiatives are being developed to define way to communicate drought information that leads to preventive actions. A particular element in the communication process is credibility so that users can act accordingly. Those who generate drought information, for instance in terms of climate or impact scenarios, must clearly document the ability and limitations of their predictions. Decisions on drought require forecasts and climate monitoring, but in the impact scenario development it is necessary to have decision makers participation. For example, precipitation forecasts may be validated with data from the climate monitoring system, but it is the water manager the one who decides on the validity of a scenario on water availability. The participation of stakeholders interested on drought information requires collaboration among climate information providers and potential users of the information.

The need for adequate communication of drought risks is of major relevance for Mexico where vulnerability to a changing climate is large. Although adaptation to climate change is in the Government and non-government planning, poor understanding of the vulnerability factors or limited awareness on the on the functioning of a sector or the capacity of decision makers have not allowed to generate successful examples on the benefits of using climate information. The challenge on documenting an end to end project on the value of using climate information among users is one of the tasks to be conducted in a drought research plan.

Summary and Conclusions

Droughts always pose difficulties for water managers, farmers and society in general. Although droughts are a recurrent natural hazard with important negative impacts in Mexico, it is not until recently that public policies are being developed to specifically address their effects. Usually, after a period of precipitation deficit and severe water scarcity, stakeholders and authorities are more sensitive to the need to be more efficient in water management and use. After the major drought in northern Mexico during the 2010-2012 period, Pronacose, as a public policy to ameliorate hydrological, agricultural or socioeconomic droughts was developed. However, such Program requires to be constructed on solid scientific basis. There are still several unsolved problems on drought that require to be addressed in order to promote pre-drought planning and investments in efficient water infrastructure, reductions in per-capita water use, more effective coordination between water agencies, and timely response to water shortages among the most vulnerable groups. In addition, water agencies and governments need to adopt, implement national drought policies, based on the principles of early warning, prepa-

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redness and risk management. It is along these lines of thought, that the Mexican Water Agency defined a National Program against Drought (Pronacose), to change a costly response to the disaster into a more efficient and less expensive prevention scheme.

An important element in the Scientific Plan to study Drought in Mexico should be the characterization of meteorological drought as a natural hazard, and hydrological, agricultural and socioeconomic drought as manifestations of precipitation deficit in a vulnerability to drought context. This means that the consequences of meteorological droughts should be diminished by means of risk management schemes, which in turn requires the adequate characterization of the vulnerability factors. The latter requires the participation of climatologists, hydrologists, agronomists, economists, social scientist, along with decision makers and stakeholders. The risk management approach to reduce the costs of drought based on a solid scientific basis should lead to the definitions of action prior to, during and after the drought conditions.

The proposed approach to generate relevant scientific drought information should be framed in a more ambitious scientific national water assessment program. As in most parts of the world, an improved strategy to manage water in general, and drought conditions in particular, should rely on:

1. Governance: organizational, legal and policy framework.
2. Risk identification, assessment, monitoring and early warning.
3. Capacity building and education.
4. Reduction of underlying risk factors.
5. Preparedness for effective response and recovery.

The planning for and the management of the effects of droughts appear to reach a higher priority in the Federal Government and apparently, in states with severe water shortages. The main goal of government policies is to reduce the costs of hydrological, agricultural and socioeconomic droughts that may be of the order of hundreds of millions of dollars in some sectors. In addition, the environmental impacts may result in the loss of large areas of natural vegetation and negative effects in other ecosystems. Reforms in the water legislation may lead Conagua to take a more proactive approach to managing the effects of droughts and spur such interest in other government agencies. Several factors will have to coexist before Pronacose becomes an effective strategy to mitigate the effects of droughts. Such factors may be the occurrence of a drought that is long and extensive, thereby increasing demands on a fixed water supply, and a public awareness of the economic costs of droughts. As water demands continue to grow, even minor droughts will become more serious, and society and socioeconomic sectors, in collaboration with the Mexican government will make Pronacose scientific research initiative an important element for improved water-management plans.

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